

Dark radiation alleviates problems with dark matter halos

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We show that a scalar and a fermion charged under a global $U(1)$ symmetry can not only explain the existence and abundance of dark matter (DM) and dark radiation (DR), but also imbue DM with improved scattering properties at galactic scales, while remaining consistent with all other observations. Delayed DM-DR kinetic decoupling eases the *missing satellites* problem, while scalar-mediated self-interactions of DM ease the *cusp vs. core* and *too big to fail* problems. In this scenario, DM is expected to be pseudo-Dirac and have a mass $100 \text{ keV} \lesssim m_\chi \lesssim 10 \text{ GeV}$. The predicted DR may be measurable using the primordial elemental abundances from big bang nucleosynthesis (BBN), and using the cosmic microwave background (CMB).

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Introduction.— Cosmological and astrophysical data now firmly point towards the existence of new *nonrelativistic* particles, dubbed dark matter (DM), and there is a vigorous experimental program underway to discover these particles and measure their properties. Dark radiation (DR), on the other hand, refers to new *relativistic* particles that contribute to the cosmological energy density but are otherwise decoupled from ordinary matter and radiation. There is neither clear evidence nor a definitive exclusion, but several independent analyses of cosmological data show tantalizing hints for DR [1–5], most recently to reconcile the results from the Planck Collaboration [6] with those from BICEP2 Collaboration [7].

Candidate particles for DR have been motivated by experimental results, e.g., additional neutrinos that explain oscillation anomalies, or to address conceptual problems in the visible sector, e.g., thermal axions that solve the strong CP problem. On the other hand, DR may have little to do with the observed particles in the Universe and instead may simply be light particles in the dark sector [8–12]. Weinberg recently presented a set-up [13], where the Goldstone bosons of a global symmetry in the dark sector lead to dark radiation, while the residual symmetry provides stability to a fermionic DM candidate. Its phenomenology has been explored in subsequent works [14–19]. In this *Letter*, we show that if DM and DR share this common origin, it may naturally solve long-standing problems in DM structure-formation.

A weakly interacting massive particle explains the cosmological abundance of DM, but there are hints from observations of dwarf galaxies and the Milky-Way that something may be lacking in this description. N-body simulations of collisionless cold DM [20] predict numerous dwarf satellite galaxies of the Milky-Way, that are not seen, viz., the *missing satellites* problem [21]. They also predict cuspy halos in dwarf galaxies where cores

are observed [22, 23], viz. the *cusp vs. core* problem, and highly massive subhalos of Milky-Way-type galaxies that would be expected to host stars, but which aren’t observed, viz., the *too big to fail* problem [24]. It has been considered that inclusion of more detailed astrophysical processes [25–33], e.g., supernova feedback, low star-formation, tidal effects, etc., or new DM physics [34–40], e.g., self-interactions, warm DM, decays/annihilations, or DM-“baryon” coupling etc., can solve *some* of these problems. Exotic interactions between DM and ordinary matter, e.g., neutrinos [41] or sterile neutrinos [42] may be able to address *all* these persistent problems. However, almost all models invoke additional physics specifically to address the small-scale problems.

We show that (i) DM scattering off the DR bath, composed of the Goldstone bosons of the global symmetry, leads to delayed kinetic decoupling that erases the least massive DM halos, which can mitigate the *missing satellites* problem, and (ii) DM self-scattering mediated by the scalar mode leads to smoothening of the inner cusps of small galactic halos, which alleviates the *cusp vs. core* and *too big to fail* problems. Together, they can ease *all* tensions between observations and cold DM simulations, with no need for any other particles or interactions. Simultaneously, the observed DM density and all other constraints can be satisfied, which predicts an observable abundance of DR and the viable DM mass-range.

In the following, we demonstrate the above mechanism. We show how the small-scale problems may be addressed, and elaborate the consequences for DR and DM. We outline the phenomenology of this scenario, and conclude with a discussion and a summary of our results.

Dark Matter and Dark Radiation.— We consider the Lagrangian for the dark sector [13, 15],

$$\begin{aligned} \mathcal{L}_{\text{dark}} \ni & \partial_\mu \phi^* \partial^\mu \phi + \mu_\phi^2 |\phi|^2 - \lambda_\phi |\phi|^4 \\ & + i \bar{\chi} \gamma^\mu \partial_\mu \chi - M \bar{\chi} \chi - \left(\frac{f_d}{\sqrt{2}} \phi \chi^T C \chi + h.c. \right), \quad (1) \end{aligned}$$

where ϕ is a complex scalar and χ is a 4-component fermion, both charged under a global $U(1)$ symmetry. After symmetry-breaking, $\phi \equiv (v_\phi + \rho + i\eta)/\sqrt{2}$ has a vacuum expectation value v_ϕ . Its CP-odd component η becomes a massless Goldstone field while its CP-even component ρ remains. At the same time, the last term in Eq. (1) splits the fermion field into two mass eigenstates χ_\pm with masses $m_{\chi_\pm} = |M \pm f_d v_\phi|$. The obvious Z_2 residual symmetry, i.e., $\chi_\pm \rightarrow -\chi_\pm$ and $(\rho, \eta) \rightarrow (\rho, \eta)$, guarantees that the lighter mass eigenstate, which we take to be χ_- , is stable, and therefore a viable DM candidate. Relativistic dark particles, e.g., the massless Goldstone mode η , yield DR.

We will be interested in DM and DR scattering processes mediated by the χ - ϕ interaction in Eq. (1), which, after symmetry breaking, is rewritten as

$$-\frac{f_d}{2}\rho(\bar{\chi}_-\chi_- - \bar{\chi}_+\chi_+) - \frac{f_d}{2}\eta(\bar{\chi}_+\chi_- + \bar{\chi}_-\chi_+). \quad (2)$$

We will show that when χ_- and χ_+ are quasi-degenerate, i.e., $m_{\chi_+} - m_{\chi_-} \equiv \Delta m_\chi \ll m_\chi$, the scattering processes can be appreciable and important. However, before we get to that, let's consider the cosmological abundances of DR and DM in this scenario.

The temperatures of the dark and the visible sectors are defined to be the temperatures of the bath of η and photons (denoted by γ), respectively. We will assume that T_\star is a temperature above which the dark sector was in thermal equilibrium with the visible sector. This may have been through processes common to both sectors at high-scale, e.g., inflaton decay. Below this temperature, the two sectors are decoupled but the conservation of entropy relates the temperatures in the two sectors as

$$T_\eta = \left(\frac{g_d^*(T_\star)}{g_d^*(T_\eta)} \frac{g_v^*(T_\gamma)}{g_v^*(T_\star)} \right)^{1/3} T_\gamma \equiv \xi T_\gamma, \quad (3)$$

where $g^*(T)$ are the effective number of relativistic degrees of freedom in the dark (d) and visible (v) sectors, respectively, at their temperatures T . In our model, $0 \lesssim \xi(T_\gamma) \lesssim 1$.

The DR density is given by relativistic particles in the dark sector, i.e., $\rho_{\text{DR}} = \pi^2 g_d^* T_\eta^4 / 30$, which is conveniently parametrized as an additional number of neutrinos species, $\Delta N_\nu \equiv \rho_{\text{DR}} / \rho_\nu = (4/7) g_d^* (T_\eta / T_\nu)^4$, using the known energy density ρ_ν of a single flavor of an active neutrino at temperature T_ν .

The DM density is set by its chemical freeze-out. In the regime of our interest (where $\Delta m_\chi \ll m_\chi$) the DM chemical freeze-out is determined by the co-annihilation process $\chi_+ \chi_- \rightarrow \rho \eta$, with the co-annihilation cross section approximately given by [15], $\langle \sigma v \rangle \simeq \alpha_d^2 \pi / m_\chi^2$, where $\alpha_d = f_d^2 / (4\pi)$. The contribution from all other channels are p -wave suppressed and subleading. The ob-

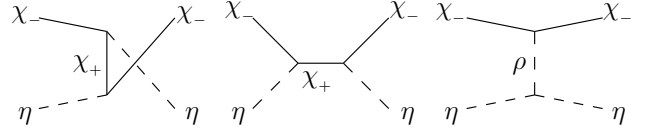


Figure 1. DM-DR scattering via u , s , and t channels.

served DM fraction $\Omega_{\text{DM}} = 0.11 h^{-2}$ is obtained for $\langle \sigma v \rangle \simeq (2-5) \times 10^{-26} \text{ cm}^3/\text{s}$ [43]. For simplicity, we neglect this variation here and take $\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3/\text{s}$, as an illustrative value. We will find that the model prefers $m_\chi \lesssim \text{GeV}$, so that the observed Ω_{DM} needs $f_d \ll 1$, which self-consistently motivates a parametric suppression of $\Delta m_\chi (\equiv 2f_d v_\phi)$.

Scattering in the Dark Sector.— The DM particle χ_- scatters with DR, i.e., the massless pseudoscalar η , through the processes shown in Fig. 1. The cross section for DM-DR scattering is

$$\sigma_{\eta\chi_-} = \frac{8\pi\alpha_d^2\omega^4}{\Delta m_\chi^6} \left(1 + \frac{16\Delta m_\chi^2}{3m_\rho^2} + \frac{8\Delta m_\chi^4}{m_\rho^4} \right), \quad (4)$$

in the limit of $\Delta m_\chi \ll m_\chi$ and where ω is the energy of η in the center-of-mass frame, roughly T_η . One can see that a small Δm_χ enhances the DM-DR scattering.

DM remains in kinetic equilibrium with DR until the momentum exchange rate due to this process becomes smaller than the Hubble expansion rate [37, 44–46], i.e., $(T_\eta/m_\chi)n_\eta\sigma_{\eta\chi_-} \sim H(T_\gamma)$, where $n_\eta = 3\zeta(3)T_\eta^3/(4\pi^2)$ is the DR number density. The above condition determines the temperature of kinetic decoupling, $T_{\text{kd}} \equiv T_\gamma|_{\text{kd}}$. We have

$$T_{\text{kd}} \simeq 0.5 \text{ keV} \frac{\delta}{10^{-4.5}} \left(\frac{m_\chi}{\text{GeV}} \right)^{7/6} \left(\frac{10^{-4}}{\alpha_d} \right)^{1/3} \xi_{\text{kd}}^{-4/3}, \quad (5)$$

where $\delta \equiv \Delta m_\chi / m_\chi$ is the fractional mass difference, and $\xi_{\text{kd}} \equiv (T_\eta / T_\gamma)|_{\text{kd}}$, which is in the range of $(0.5 - 0.8)$. DM-DR scattering can lower T_{kd} , which enhances the acoustic damping cutoff, M_{cut} , in the structure power spectrum. Quantitatively [47], we have $M_{\text{cut}} \simeq 1.7 \times 10^8 (T_{\text{kd}}/\text{keV})^{-3} M_\odot$, such that $T_{\text{kd}} \simeq 0.5 \text{ keV}$ suppresses formation of DM protohalos smaller than about $10^9 M_\odot$, and eases the *missing satellites* problem [48]. It is important to note that the acoustic damping cut-off in our model is different in shape (oscillatory, with power-law envelope) [49, 50], from the free-streaming cut-off in warm dark matter models (exponential). As a result, Lyman- α and other constraints on warm dark matter [51, 52] cannot be applied directly [49, 50].

DM particles can scatter with each other via $\chi_- \chi_- \leftrightarrow \chi_- \chi_-$, mediated by the scalar ρ . The t and u channel amplitudes dominate the self-scattering due to the smallness of the energy transfer. In the nonrelativistic limit, the squared-matrix element is approximately $|iM|^2 \simeq$

$4m_\chi^4/m_\rho^4$, and the interaction is better described by an attractive Yukawa potential $V(r) = -(\alpha_d/r)e^{-r/m_\rho}$, whose cross section has been studied extensively in the literature [53–55]. For instance, in the Born regime, $\alpha_d m_\chi/m_\rho \ll 1$, the scattering cross section in the center of mass frame, $\sigma_T = \int d\Omega (d\sigma/d\Omega)(1 - \cos\theta)$, is given by [54]

$$\sigma_T \simeq \frac{8\pi\alpha_d^2}{m_\chi^2 v_{\text{rel}}^4} \left[\log(1 + R^2) - \frac{R^2}{1 + R^2} \right], \quad (6)$$

with $R \equiv v_{\text{rel}} m_\chi/m_\rho$. Here, v_{rel} is the relative velocity of the two colliding DM particles. We use σ_T in the nonperturbative and resonant regimes from Ref. [55].

The self-scattering of DM can address the other two small-scale problems of DM. N-body simulations show that $\langle\sigma_T\rangle/m_\chi \sim (0.1 - 1) \text{ cm}^2/\text{g}$ at $v_{\text{rel}} \sim 10 \text{ km/s}$ leads to smoothening of the inner $\sim 1 \text{ kpc}$ of DM halos in dwarf galaxies and mitigates the *cusp vs. core* problem [56, 57]. Here, $\langle\dots\rangle$ denotes an average over the velocity distribution, which we take to be of the Maxwell-Boltzmann form with dispersion v_{rel} . The same effect also tends to make the inner region of dwarf-sized dark matter halos less dense, and is able to alleviate the *too big too fail* problem [57, 58]. On the other hand, observations of colliding galaxy clusters, e.g., the Bullet cluster, do not show evidence for DM-DM interactions and thus require $\langle\sigma_T\rangle/m_\chi < 1 \text{ cm}^2/\text{g}$ at typical velocities of $v_{\text{rel}} \sim 10^3 \text{ km/s}$ therein [59]. An ab initio calculation, including the above effects, will provide a more detailed and quantitative prediction of the small-scale structure.

In Fig. 2, we show the parameter space where the observed DM abundance is obtained through its chemical freeze-out and all the small-scale problems of DM structure-formation are solved simultaneously. For a given DM mass, the relic density fixes α_d (shown on the top x-axis). To solve the *cusp vs. core* and *too big too fail* problems, one needs $\langle\sigma_T\rangle/m_\chi \sim (0.1 - 1) \text{ cm}^2/\text{g}$ at $v_{\text{rel}} \sim 10 \text{ km/s}$, which determines m_ρ in terms of m_χ (shaded band). The oscillatory behavior comes from resonances in the DM scattering. To mitigate the *missing satellites* problem the DM-DR scattering must be enhanced through a near-degeneracy of the masses of χ_\pm . The corresponding value of δ , which leads to $T_{\text{kd}} = 0.5 \text{ keV}$ and hence to $M_{\text{cut}} \simeq 10^9 M_\odot$, is shown through a color-gradient inside the band. We also show the constraint from the galaxy clusters that $\langle\sigma_T\rangle/m_\chi < 1 \text{ cm}^2/\text{g}$ for $v_{\text{rel}} \sim 10^3 \text{ km/s}$ (hatched region at the bottom is ruled out), and that the theory for the complex scalar ϕ is perturbative, i.e., $\lambda_\phi/(4\pi) \lesssim 1$ (below dashed line).

Some comments are in order about the scenario we identify above. If $m_\chi \lesssim 100 \text{ keV}$, DM is no longer a truly cold relic, and δ is no longer small. Also, m_ρ becomes light enough that it directly contributes to DR around T_{kd} . On the other hand, if $m_\chi \gtrsim 10 \text{ GeV}$ the potential for

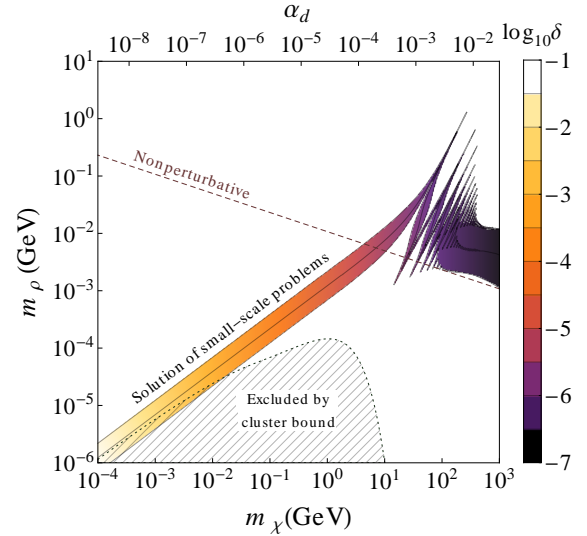


Figure 2. Solution of all small-scale problems of DM. For a DM mass m_χ , the coupling α_d (top x-axis) is determined by the relic density. Small-scale problems are solved within the band. Three thin solid lines in the band correspond to $\langle\sigma_T\rangle/m_\chi \sim 0.1, 1, 10 \text{ cm}^2/\text{g}$, respectively (top-down), at $v_{\text{rel}} \sim 10 \text{ km/s}$, addressing the *cusp vs. core* and *too big too fail* problems. The color-gradient inside shows the common logarithm of $\delta \equiv \Delta m_\chi/m_\chi$, which leads to $T_{\text{kd}} = 0.5 \text{ keV}$ and solves the *missing satellites* problem. The hatched region at the bottom shows the constraint from galaxy clusters, $\langle\sigma_T\rangle/m_\chi \lesssim 1 \text{ cm}^2/\text{g}$ at $v_{\text{rel}} \sim 10^3 \text{ km/s}$, while the dashed line indicates the largest m_ρ for which the scalar potential for ϕ is perturbative.

ϕ is no longer perturbative. We therefore find $100 \text{ keV} \lesssim m_\chi \lesssim 10 \text{ GeV}$ to be best-motivated.

Predictions and Constraints.— The previous considerations show that the complete scenario is specified in terms of the DM mass if we require that the small-scale problems of DM be resolved. This has two interesting and generic consequences – (i) DR leads to an observable prediction for ΔN_ν , and (ii) m_χ is predicted in the $100 \text{ keV} - 10 \text{ GeV}$ range, which may be testable at colliders and direct detection experiments aimed at light DM.

Fig. 3 shows the prediction for ΔN_ν in BBN and CMB epochs. ΔN_ν increases with a later decoupling, i.e., lower T_\star , because the decaying SM particles heat up the dark sector as well. This is most apparent for $T_\star \lesssim 0.2 \text{ GeV}$, i.e., below the QCD crossover. There is also a signature *step-like* dependence on m_χ , because of energy injection in the dark sector from m_χ and m_ρ decays. If $m_\chi > T_\star$, then DM freeze-out heats up both the visible and dark sectors and effectively lowers ΔN_ν . On the other hand, if m_χ and/or $m_\rho \simeq 10^{-3} m_\chi \gtrsim T_{\text{BBN}} \simeq 1 \text{ MeV}$, then the DR bath is heated up by their annihilations/decays, increasing ΔN_ν at BBN. These effects lead to sharp changes in ΔN_ν across the mass thresholds. Such an effect also exists for ΔN_ν at CMB, however for much smaller masses of m_χ and m_ρ not relevant here. Note

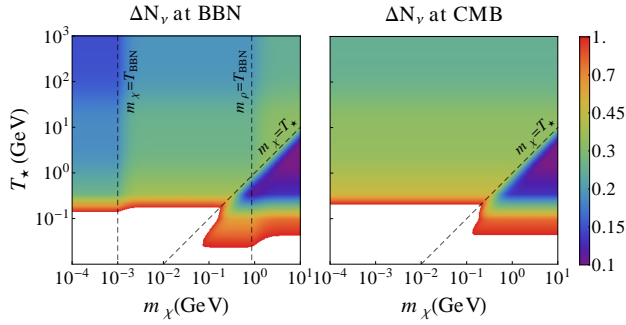


Figure 3. ΔN_ν generated by dark radiation, depending on the DM mass m_χ and the temperature T_\star at which the dark and visible sectors decoupled. The white area denotes $\Delta N_\nu \geq 1$.

also, that there is a minimum DR abundance predicted, i.e., $\Delta N_\nu \simeq 0.13$. Dark acoustic oscillations may also constrain this scenario [60].

The connection between the dark sector and the Standard Model (SM) is through the mixing of the dark scalar ϕ with the SM scalar doublet Φ , via $\kappa|\phi|^2|\Phi|^2$. After symmetry breaking, for $m_\rho/m_h \ll 1$, this can be parametrized as a mass-mixing between the dark scalar ρ and the SM Higgs h , via a small mixing angle $\theta \simeq \kappa v_\phi v_{SM}/m_h^2$.

The ϕ -Higgs mixing is probed in three independent and complementary ways, as shown in Fig. 4. (i) ΔN_ν increases due to the thermalization of the dark sector with the visible sector through $\eta\eta \leftrightarrow \text{SM SM}$. This sets an upper bound $\kappa \lesssim 0.01$, if we require $\Delta N_\nu \lesssim 1$ [3, 61]. If the small-scale problems are to be addressed successfully, this translates to $f_d |\sin \theta| \lesssim 3.2 \times 10^{-9} (m_\chi/\text{GeV})^{1/6}$ (gray line). Note that for $m_\chi \gtrsim 0.1 \text{ GeV}$ and $m_\chi > T_\star$, one predicts a smaller ΔN_ν as shown in Fig. 3, and the bound is weakened significantly. (ii) Invisible decays of the h to ρ or η at colliders also probe the same coupling and set an upper bound [62, 63] that is translated to $f_d |\sin \theta| \lesssim 4.7 \times 10^{-9} (m_\chi/\text{GeV})^{1/6}$ (blue line). These two bounds are comparable, and in future more pre-

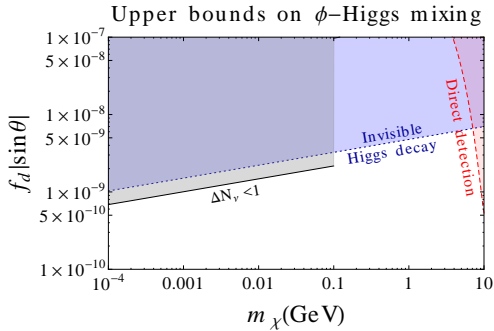


Figure 4. Experimental upper bounds on the scalar mixing of ϕ and Higgs. Values of m_ρ and f_d have been chosen to solve the small-scale problems. The shaded region has been excluded by either DM direct detection (dashed red), invisible Higgs decay (dotted blue), or bounds on ΔN_ν (solid gray).

cise measurements of Higgs decay at colliders will probe the regime with a sub-GeV m_χ . (iii) The bounds on the DM-nucleon cross section from present experiments, e.g., SuperCDMS and LUX [64, 65], are sensitive for m_χ in the (few – 10) GeV range, and give an upper limit $f_d |\sin \theta| \lesssim 0.5 \times 10^{-7}$ at 4 GeV (red line), degrading exponentially with smaller DM masses. In the (7 – 10) GeV range, direct detection is marginally more sensitive than colliders or cosmology, and may detect a DM signal. Encouragingly, planned direct detection experiments will probe this scenario more sensitively [66, 67].

Discussion and Summary. – We have shown that a complex scalar and a fermion charged under a global $U(1)$ symmetry can not only explain the existence and abundance of DM and DR, but also imbue DM with improved scattering properties at galactic scales. This mechanism doesn’t require any ad hoc particles or interactions, has the minimal structure required, and is conceptually simpler compared to previous approaches [41, 42, 68, 69] to this persistent and well-studied problem.

One important aspect of our work is identification of the helicity properties of the scattering amplitudes. It was known that scalar-mediated scattering of DM off a bath of light fermions can’t produce late kinetic decoupling [41]. A bath of dark massless gauge bosons is also prevented from delaying DM kinetic decoupling to $T \lesssim \text{keV}$ if ellipticity bounds on galaxies apply [70]. We showed that these limitations can be overcome if the bath is composed of a pseudoscalar instead. The Goldstone mode of the spontaneously broken $U(1)$ provides such a pseudoscalar that delays DM kinetic decoupling, while the scalar mode enhances DM self-scattering.

Phenomenologically the idea is viable and testable. The specific scenario we identified, i.e., the pseudo-Dirac DM regime of Ref. [13], addresses the small-scale problems of DM, and we explored reheating effects in the dark sector. The main signatures are a light DM, in the 100 keV – 10 GeV range, and peculiar patterns for ΔN_ν , e.g., BBN abundances may show a ΔN_ν that’s smaller than in CMB measurements. This is due to annihilations and decays of χ_- and/or ρ , as shown in Fig. 3. The connection to the SM may be probed at colliders, future direct detection experiments, and using precise cosmological measurements of ΔN_ν , etc. [60]. On the other hand, absence of an appreciable abundance of DR, e.g., measuring $\Delta N_\nu \lesssim 0.13$ in the CMB epoch, would rule-out this scenario. The possibility, that the nature of DM and DR and their shared symmetry could be inferred via their consequences on astrophysical structures, and revealed cosmologically, is nonetheless remarkable.

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